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ADVANCES IN THE ASSESSMENT OF THE LOCAL SEISMOLOGICAL MAGNITUDE SCALE M_L FOR VENEZUELA

AVANCES EN LA ESTIMACIÓN DE UNA ESCALA DE MAGNITUD SISMOLÓGICA LOCAL M_L PARA VENEZUELA

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ABSTRACT

In this study we determined local magnitude scales M_L for Venezuela for vertical (Z) and horizontal seismological components (N-S y E-W), respectively, recorded by the National Seismological Network. We measured 636 vertical and horizontal peak amplitude data for 50 inland earthquakes which occurred between 2006 and 2012, that were recorded by 35 broadband stations of the National Seismological Network. The focal depths were shallow (up to 25 km) and the magnitude range was from 3.4 to 5.7 M_w. We found a good correlation between maximum amplitudes on the vertical component and those on the horizontal component. The average of the ratio of the horizontal component amplitude to the vertical component amplitude was 1.7. The local magnitude coefficients for geometrical spreading and anelastic attenuation obtained by linear inversion were 1.031 and 0.00116 for the vertical component, and 1.306 and 0.00075 for the horizontal component, respectively. The magnitude residuals calculated for the local magnitude formulas obtained in this study did not show significant dependence on the hypocentral distance. We compared local magnitudes for both components and found that the local magnitude for the vertical component was smaller than that for the horizontal component by about 0.2 in the magnitude range from 3.2 to 5.5. The distance corrections for Venezuela at the distance range larger than 100 km are lower than that for Southern California, which is adopted for the International Association of Seismology and Physics of the Earth's Interior (IASPEI) standard formula.

KEY WORDS: National Seismological Network, anelastic attenuation, geometrical spreading.

RESUMEN

El trabajo consistió en estimar los coeficientes de la ecuación de magnitud local M_L para Venezuela asociadas a las componentes vertical (Z) y horizontales (N-S y E-O), respectivamente, registrados por la Red Sismológica Nacional. Un total de 636 amplitudes máximas fueron medidas en 50 sismos continentales ocurridos en el período 2006-2012. Las profundidades de estos sismos fueron superficiales, con intervalos de magnitud entre 3,4 y 5,7 M_w. Se encontró una buena correlación entre las amplitudes máximas de ambas componentes, con un valor medio del cociente entre la amplitud máxima de las componentes horizontales sobre la componente vertical igual a 1,7. Los coeficientes de la ecuación de la magnitud local relacionados con la dispersión geométrica y la atenuación anelástica obtenidas a través de métodos de inversión lineal, fueron 1,031 y 0,00116 para la componente vertical y 1,036 y 0,00075 para las componentes horizontales. Los residuos de las ecuaciones de magnitud local obtenidos en este estudio no mostraron dependencia significativa con relación a la distancia hipocentral. Se compararon las ecuaciones de magnitud local de ambas componentes y se obtuvo que la magnitud local para la componente vertical es menor que aquella obtenida para las componentes horizontales por aproximadamente 0,2 en el intervalo de magnitud 3,2 a 5,5. La curva de atenuación asociada a Venezuela, correspondiente a distancias superiores a los 100 kilómetros, mostró valores inferiores a los propuestos en el sur de California, la cual se adopta como la fórmula estándar por la Asociación Internacional de Sismología y Física del Interior de la Tierra.

PALABRAS CLAVE: Red Sismológica Nacional, atenuación anelástica, dispersión geométrica.

INTRODUCTION

An early seismic network in Venezuela became operational in 1980 and consisted of 12 short-period instruments located in the north-central region. After the 1997 Cariaco earthquake (Romero *et al*. 1998), the National Seismological Network was upgraded and 35 broadband three-component stations have been installed along the main faults (Romero *et al*. 2003). Since the deployment of this new seismic network in 2000, the number of recorded earthquakes has increased from a few hundred to a few thousand events per year (Fig. 1). This indicates that our capacity to record the seismic activity in the country has significantly improved.

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The national network instruments operate in continuous-recording mode. The network is equipped with an automatic earthquake detection system which is followed by manual verification. The data recorded by the National Seismological Network is used to generate monthly seismological bulletins and a high-quality earthquake dataset is constantly updated.

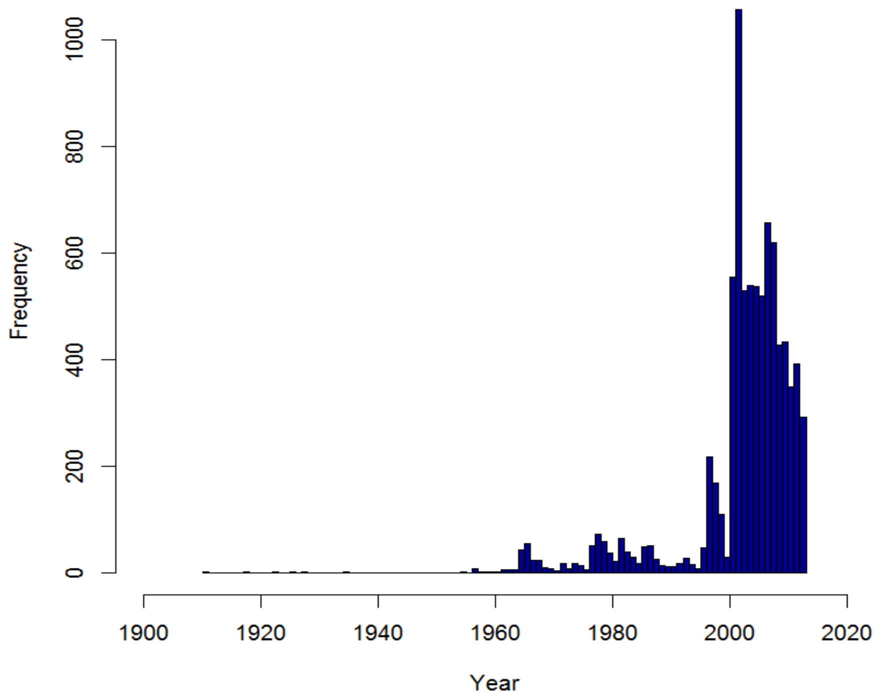

Figure 1. Number of earthquakes as a function of time for the period 1910-2013 from the catalogue of the Venezuelan Foundation for Seismological Research (FUNVISIS).

Information regarding magnitude scales in the catalogue of FUNVISIS is from three different periods: (*1*) before installation of the first seismological network in the 1980's, the information comes from international sources such as the ISS, ISC, USGS and others, mostly body wave magnitude (m_b) and surface wave magnitude (M_s); (*2*) between 1980 and 1999, the magnitude scale used for earthquakes recorded by the network located in the north-central region was m_b, and (*3*) from the very beginning of the broadband network in 2000, coda (M_C) and moment (M_w) has been used to determine earthquake magnitudes.

It is important to determine a local magnitude M_L for earthquakes in Venezuela because most of them are less than magnitude 4.0, and because it is difficult to determine M_w for small events (say $M < 2.0$) due to higher noise levels at low frequencies. Richter (1935, 1958) defined M_L to be a logarithm of the maximum zero to peak amplitude A that would be recorded at an epicentral distance of 100 km on a Standard Wood-Anderson torsion seismograph. Although it is not directly related to physical parameters such as seismic moment, M_L is important in quantifying the seismicity rate and the distance attenuation for a given region (Hutton and Boore 1987, Kanamori and Jennings 1978).

The aim of this study is to determine coefficients for a local magnitude scale for Venezuela using recent data from the National Seismological Network. The new local magnitude scale will indicate the general characteristics of seismic wave propagation and attenuation beneath the northern part of the country.

METHOD

In this study, the approach of Miao and Langston (2007) was used in order to estimate the coefficients for the distance-correction function for the local magnitude scale. In Richter definition (1935, 1958), the local magnitude scale is given by a Standard Wood-Anderson torsion seismograph as:

$$M_L = \log A - \log A_0 + S \tag{1}$$

Where A is the maximum trace amplitude observed on the horizontal component, A_0 is the amplitude for a reference event at a certain distance and S is the station correction factor. The term –log A_0 in Eq. (1) is consider a distance-correction function, assuming that the magnitude of an event recorded at an epicentral distance of 100 km will be 3.0 if the maximum amplitude is 1 *mm*.

Hutton and Boore (1987) suggest that Eq. (1) can be expressed as:

$$-\log A_{ij} = n\log\left(\frac{r_{ij}}{100}\right) + K\left(r_{ij} - 100\right) + 3.0 - M_{Li} + S_j \qquad (2)$$

Where n and K are parameters related with geometrical spreading and anelastic attenuation, A_{ij} is horizontal maximum amplitude of the ith event observed at the jth station, r_{ij} is the hypocentral distance from the ith event to the jth station component, M_{Li} is the local magnitude of the ith event and S_j is the correction factor for the jth station.

Miao and Langston (2007) reconfigure Eq. (2) as:

$$-n\log\left(\frac{r_{ij}}{100}\right) - K\left(r_{ij} - 100\right) + M_{Li} - S_j = \log A_{ij} + 3.0 \qquad (3)$$

A set of Eq. (3) for pairs of earthquakes and stations can be expressed by a standard matrix formation:

$$\mathbf{Gm} = \mathbf{d} \qquad (4)$$

In this study, we did not determine a correction factor for station S_j due to the limited size of the dataset. For p number of earthquakes and q number of station components, the matrix **G** and vectors **m** and **d** are given explicitly as:

$$\mathbf{G} = \begin{bmatrix} -\log\left(r_{11}/100\right) & -\left(r_{11} - 100\right) & 1 & 0 & \cdots & 0 \\ -\log\left(r_{12}/100\right) & -\left(r_{12} - 100\right) & 1 & 0 & \cdots & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ -\log\left(r_{p(p-1)}/100\right) & -\left(r_{p(p-1)} - 100\right) & 0 & \cdots & 0 & 1 \\ -\log\left(r_{pq}/100\right) & -\left(r_{pq} - 100\right) & 0 & \cdots & 0 & 1 \end{bmatrix}_{pq\times(p+2)} \qquad (5)$$

$$\mathbf{m} = \begin{bmatrix} n \\ K \\ M_{L1} \\ \vdots \\ M_{Li} \end{bmatrix}_{(p+2)\times 1} \qquad (6)$$

$$\mathbf{d} = \begin{bmatrix} \log A_{11} + 3.0 \\ \log A_{12} + 3.0 \\ \vdots \\ \log A_{p(q-1)} + 3.0 \\ \log A_{pq} + 3.0 \end{bmatrix}_{pq\times 1} \qquad (7)$$

As stated in Miao and Langston (2007), Eq. (4) can be solved using methods such as least-squares and maximum likelihood. By solving this equation we can estimate the unknown model parameters within the vector **m** using the amplitude measurements included in vector the **d** and hypocenter distances included in kernel matrix **G**.

In Richter's (1935, 1958) original conception, horizontal components were used to measure maximum amplitudes for M_L. Currently, IASPEI (2005, 2013) recommend distance correction based on Hutton and Boore (1987) for crustal events located in regions with attenuation characteristics similar to Southern California for maximum amplitudes from the horizontal component. Instead, for crustal events located in regions with attenuation characteristics different from those of Southern California, it is recommended that maximum amplitudes may be measured from vertical components.

When seismological stations are located on rock, maximum amplitudes of vertical and horizontal components are similar (Havskov and Ottemöller 2010). This was tested in South Africa (Saunders *et al*. 2012) by estimating the mean value of the vertical to horizontal component ratio. They obtained a ratio of 0.94 with a correlation coefficient of 0.96. The log amplitudes from the vertical and horizontal components were in good agreement.

On the other hand, Alsaker *et al*. (1991) found small differences between maximum amplitudes of vertical and horizontal components in Norway. Amplification of the horizontal component record is more pronounced at stations located on soil, whereas the vertical component record is less affected (Havskov and Ottemöller 2010). Havskov and Ottemöller (2010) recommend using vertical component rather than horizontal component to measure maximum amplitudes in order to estimate local magnitude, since this would provide more consistent results.

NETWORK AND DATA

We used waveform data recorded by 35 broadband stations from the National Seismological Network operated by FUNVISIS (Fig. 2). The broadband seismic stations are equipped with GURALP sensors of the type CMG-40T; they are three component sensors characterized by a flat velocity response in the period range of 0.02-33.0 s. The three channels are dedicated to transmit the three components of the ground motion detected by the broadband sensor. Data is transmitted by satellites. Each station broadcasts continuously with a rate of 100 samples/s to the central site in FUNVISIS, which is located in Caracas, the capital city.

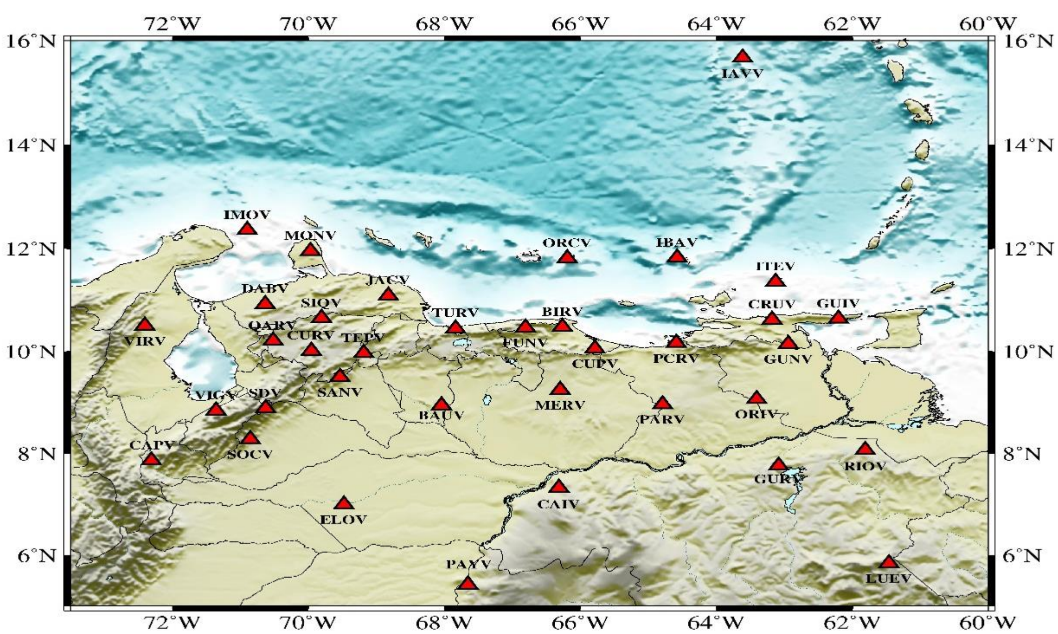

Figure 2. The solid red triangles denote the distribution of the National Seismological Network stations.

To obtain amplitudes for the vector **d**, we conducted the following three steps: (*1*), removal of instrument response from waveforms using deconvolution, (*2*), convolution of the frequency response of a Standard Wood-Anderson torsion seismograph (free period T_0 = 0.8 s, magnification of 2800 and damping of 0.8) and (*3*), measurement of peak amplitude in the horizontal and vertical components.

We selected a set of 50 inland earthquakes that were recorded between 2006 and 2009, within an area bounded by coordinates 8° to 12° N and 71.5° to 62° W. The location of epicenters and focal depths are shown in Figure 3. The epicentral distance range was from 7 to 1100 km. The magnitude range was from 3.4 to 5.7 M_w. The focal depths were up to 25 km. Since the year 2000 the HYPOCENTER (Lienert *et al*. 1986, Lienert 1991, Lienert and Havskov 1995) routine within SEISAN (Havskov and Ottemöller 1999) has been used in order to determine hypocenters. Moment magnitude was computed, applying spectral analysis (Brune 1970). Figure 4 shows the number of earthquakes as a function of depth and magnitude.

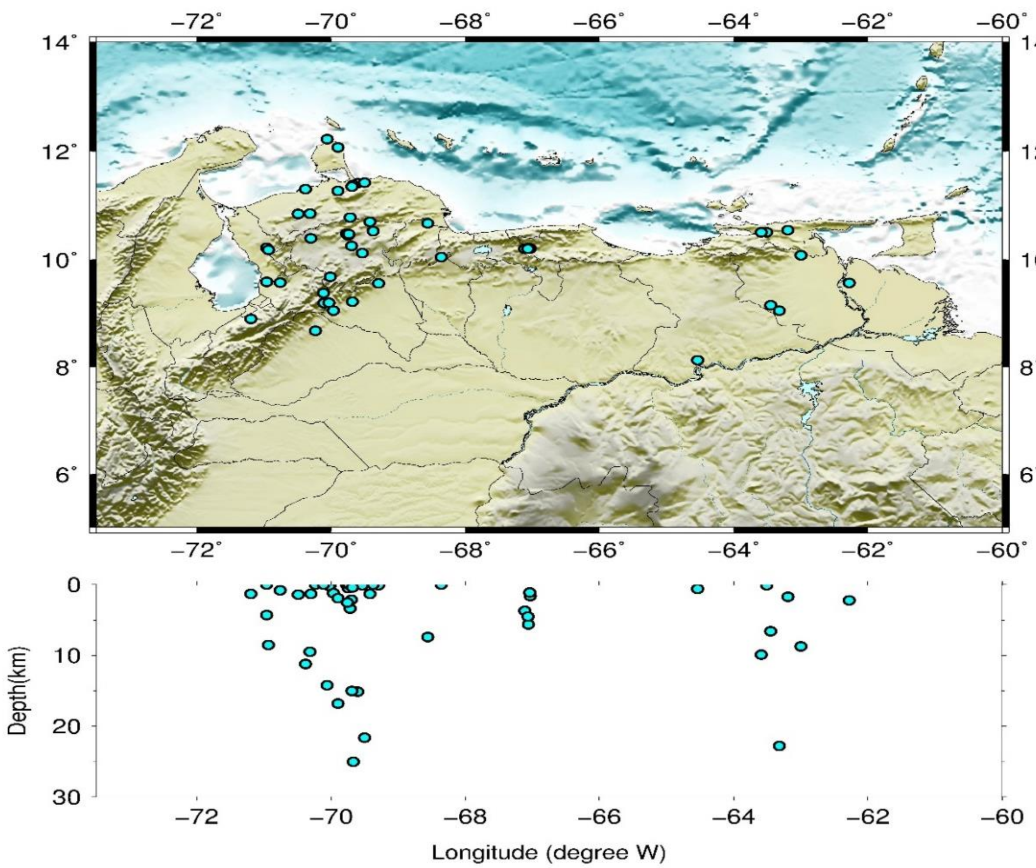

Figure 3. The epicenter and focal depths of the earthquakes used in this study.

636 amplitude measurements were obtained for both horizontal and vertical components using SEISAN (Havskov and Ottemöller 1999). Only waveforms recorded with enough time to measure the maximum amplitude were considered. Displacement amplitudes of the horizontal and vertical components were obtained by deconvolution of the waveform from the instrument response, and the resulting ground displacement waveform convolved with the frequency response of the standard Wood-Anderson torsion seismograph. The filtering required for this data processing is implemented in SEISAN (Havskov and Ottemöller 1999). It is recognized that the most likely gain of the standard Wood-Anderson torsion seismograph is 2080 rather than the originally assumed 2800 (Urhammer and Collins 1990). In this study we used 2800 following Miao and Langston (2007).

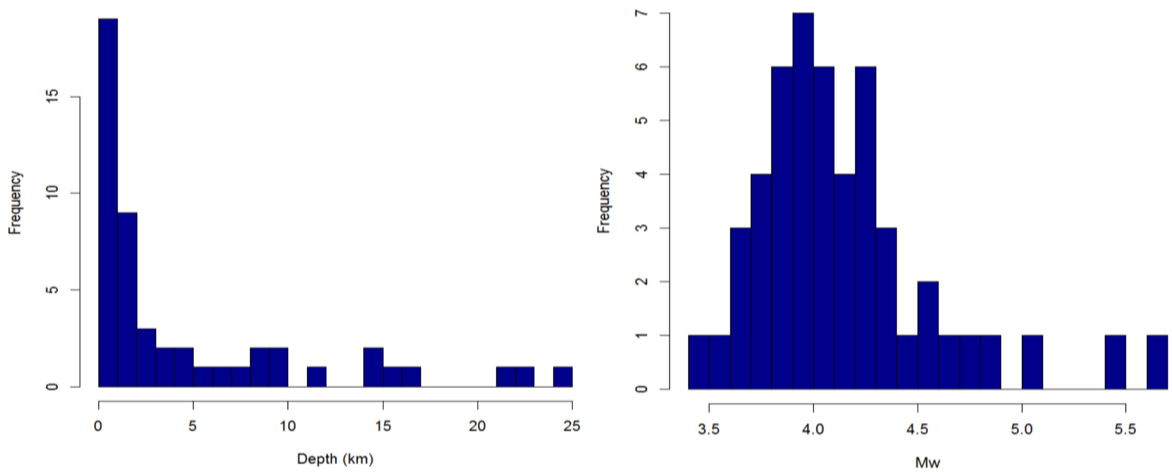

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Figure 4. (a) Number of earthquakes as a function of depth and (b) Number of earthquakes as a function of magnitude.

RESULTS AND DISCUSSION

Amplitudes on vertical and horizontal components

In this study maximum amplitudes were measured for both vertical and horizontal components, respectively. They are referred to A_V and A_H, respectively. Figure 5 shows a comparison between A_V and A_H and they correlate well.

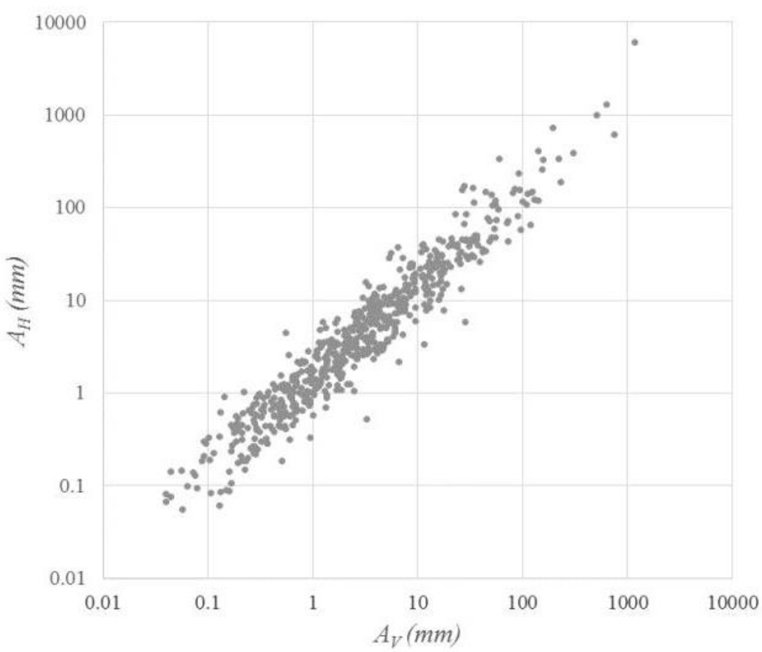
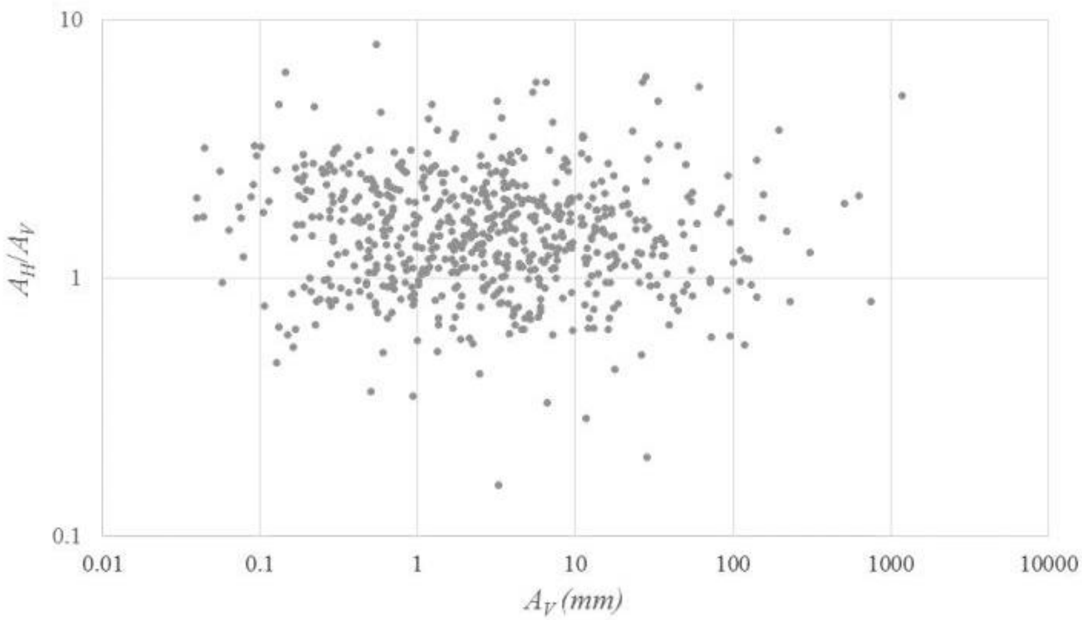


Figure 5. Comparison between maximum amplitudes on horizontal and vertical components of the dataset used in this study.

The ratio of the horizontal component amplitude to the vertical component amplitude (A_H/A_V) was calculated. Figure 6(a) shows the ratios and their frequency distribution. Scattering of the A_H/A_V ratio with respect to A_V was relatively small. The average of the A_H/A_V ratio is 1.68 and the standard deviation is 0.93; in most cases the horizontal component amplitudes are greater than vertical component amplitudes. Figure 6(b) is the histogram of the A_H/A_V ratio with variation mostly between 0.5 and 3.25. Approximately 79.6% of data are included in the range between 0.5 and 2.25.



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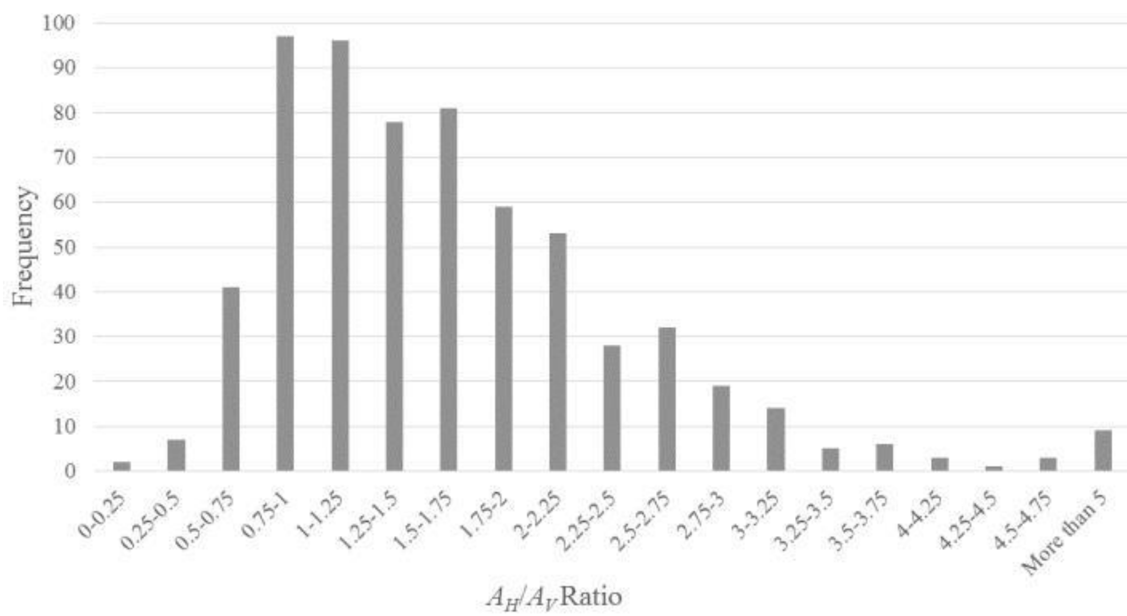

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Figure 6. (a) A_H/A_V ratio as a function of vertical component and (b) Histogram of A_H/A_V ratio.

Coefficients for local magnitude scale

In this study a linear inversion under constraints (Jackson 1979) was conducted to determine the distance-correction function given by Eq. (2) for each of the vertical and horizontal components. From previous studies (IASPEI 2005, 2013), Eq. (9.32), Lay and Wallace (1995), we set 3 and 0.002 for the standard deviations of n and K, respectively. According with the magnitude distribution of the dataset for this study (Fig. 4b), we set 4.5 for the standard deviations of M_L. The local magnitude formulas for Venezuela obtained from the inversions are:

$$M_L^{(V)} = \log(A_V) + 1.031 \log(r/100) + 0.00116\ (r\text{-}100) + 3.0 \qquad (8)$$

$$M_L^{(H)} = \log(A_H) + 1.306 \log(r/100) + 0.00075\ (r\text{-}100) + 3.0 \qquad (9)$$

Where $M_L^{(V)}$ and $M_L^{(H)}$ are local magnitude for vertical and horizontal components, respectively, A_V and A_H are the maximum amplitudes (in *mm* with magnification of 2800) observed for vertical and horizontal components, respectively, and r is the hypocentral distance in km. The errors obtained from the inversions are about 0.31 and 0.00054 for n and K, respectively, for both components.

The distance-correction functions are:

$$-\log A_0^{(V)} = 1.031 \log(r/100) + 0.00116\ (r\text{-}100) + 3.0 \qquad (10)$$

$$-\log A_0^{(H)} = 1.306 \log(r/100) + 0.00075\ (r\text{-}100) + 3.0 \qquad (11)$$

Where $A_0^{(V)}$ and $A_0^{(H)}$ are the distance correction function for vertical and horizontal components, respectively.

Local magnitudes for vertical and horizontal components according to the coefficients obtained through the inversions are compared in Figure 7. They correlate well with slight systematic differences due to differences between maximum amplitudes of both components.

We estimated the relation between $M_L^{(V)}$ and $M_L^{(H)}$ by applying the least squares method and obtained $M_L^{(V)} = 1.034 M_L^{(H)} - 0.32$. The local magnitude for the vertical component was smaller than that for the horizontal component by about 0.2 in the magnitude range from 3.2 to 5.5. Figure 8 shows the comparison between the observed amplitudes and the amplitudes calculated for vertical and horizontal components. For both components they correlate well.

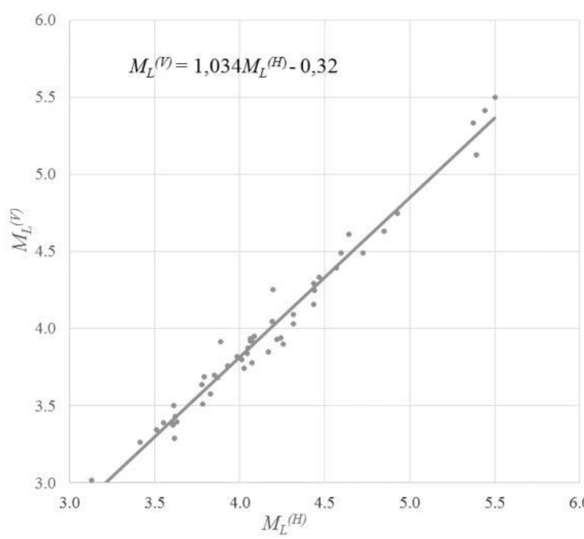

Figure 7. Comparison between local magnitudes obtained for vertical and horizontal components. The orange line delineates linear regression of data.

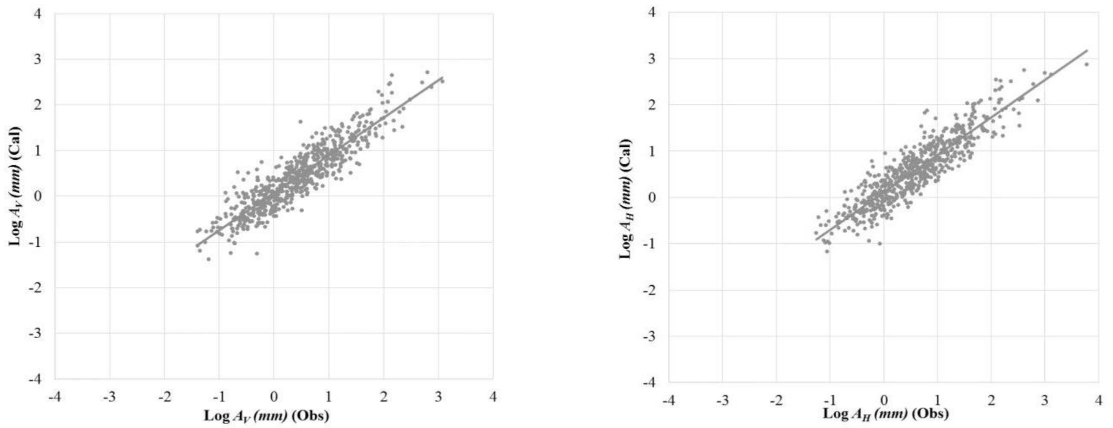

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Figure 8. Comparison between the logarithms of calculated and observed amplitudes for vertical (a) and horizontal (b) components. The orange line delineates linear regression of data.

Residuals

Figure 9 shows the local magnitude residuals as a function of hypocentral distance and the histograms of residuals for each of the vertical and horizontal components. The residuals are the difference between a local magnitude for a station for a particular earthquake and the mean value for the same earthquake.

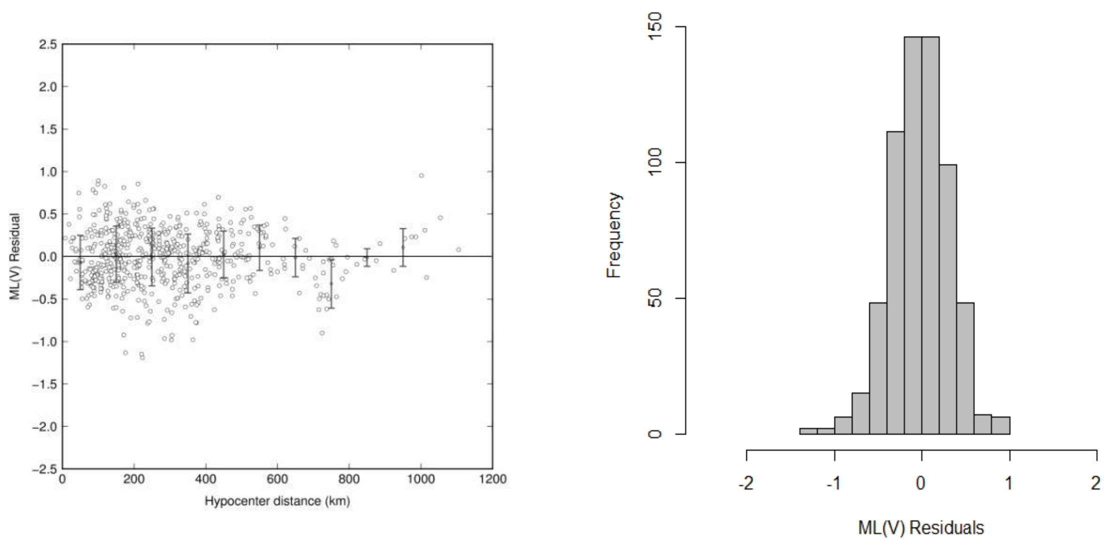

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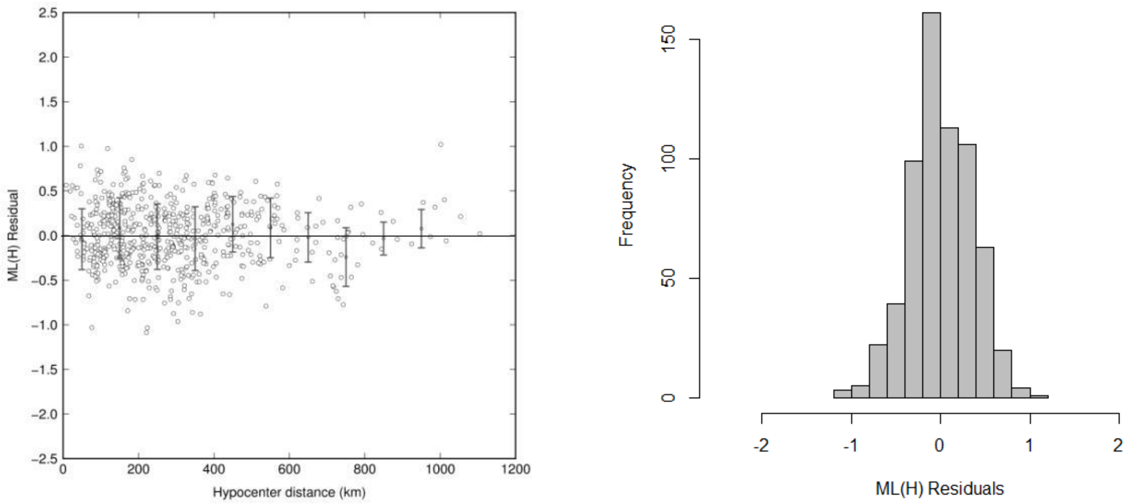
Figure 9. Distribution of M_L residuals for vertical component as a function of hypocenter distance (a) and their histogram (b).



c d

Figure 9. Distribution of M_L residuals for horizontal component as a function of hypocenter distance (c) and their histogram (d).

The distribution of residuals do not show a dependence on the hypocentral distance, at least up to 700 km. The mean value and associated standard deviation (the circles and bars in Figure 9) for every 100 km epicentral distance range followed the zero baseline closely. This trend indicates that the relation between attenuation and hypocenter distance in the region were accurately modeled with our attenuation curve. The mean values of residuals for vertical and horizontal components are 4.22×10^{-17} and 5.59×10^{-18}, respectively. The standard deviation of residuals for vertical and horizontal components are 0.33 and 0.34, respectively.

Attenuation curve

Figure 10 shows the attenuation curves obtained in this study for vertical and horizontal components, Southern California (Hutton and Boore 1987), Central California (Bakun and Joyner 1984), Central United States (Miao and Langston 2007) and Norway (Alsaker *et al*. 1991). We found that for distances beyond 100 km, the attenuation in Venezuela is lower than those in Central and Southern California, and higher than in the central United States and Norway.

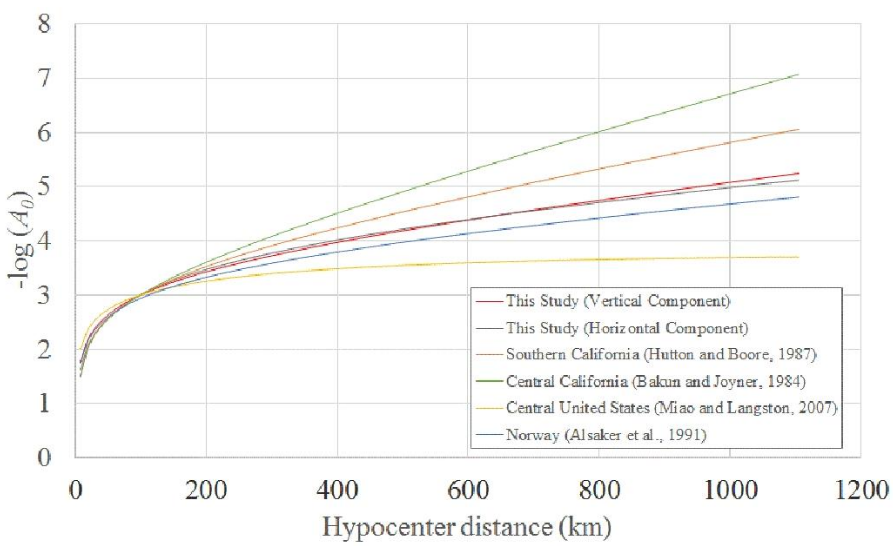


Figure 10. Comparison of attenuation curves.

We calculated local magnitudes using the distance correction of the IASPEI standard (the coefficients are from Hutton and Boore 1987) and compared local magnitudes calculated by Eq. (8) and Eq. (9) for vertical and horizontal components (Fig. 11). Both magnitudes correlate well. We found that when the IASPEI formula is used, M_L are slight overestimates.

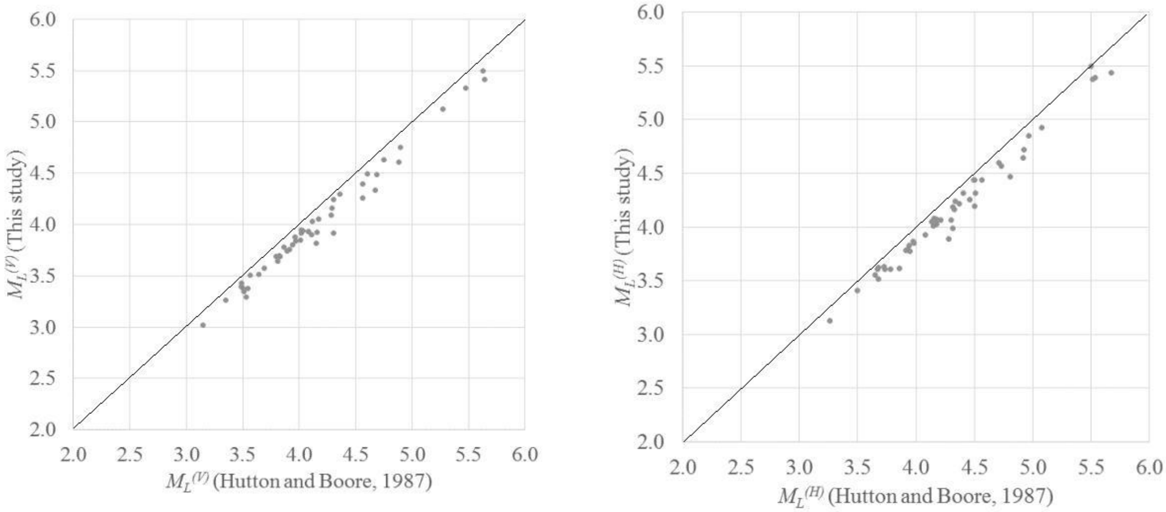


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Figure 11. Comparison between M_L calculated by the formulas obtained by this study and those calculated using the distance correction for IASPEI standard for vertical (a) and horizontal (b) components.

Figure 12 shows the local magnitude residuals when the IASPEI standard formula is used as a function of hypocentral distance. In this case, we found that the distribution of the residuals show a dependence on the hypocentral distance.

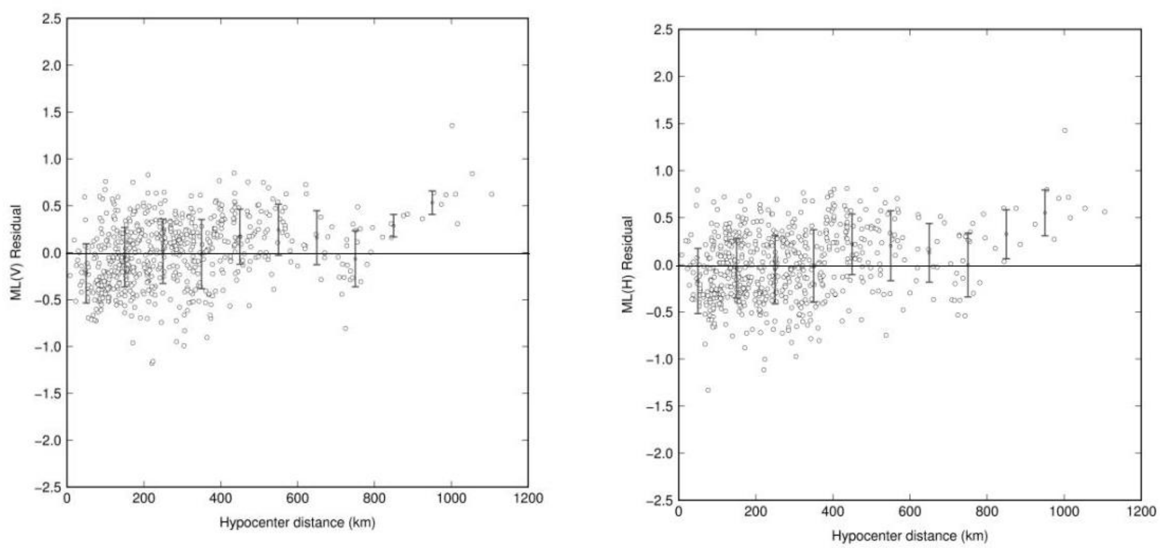

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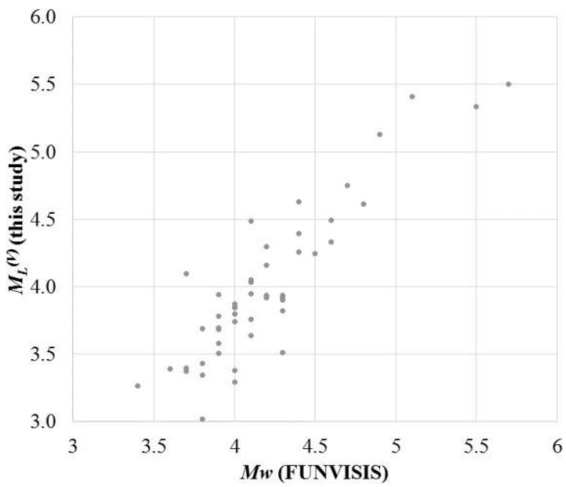
Figure 12. Distribution of M_L residuals using distance correction function of the IASPEI standard formula for vertical (a) and horizontal (b) components as a function of hypocentral distance.

Comparison between magnitude scales

The local magnitudes obtained in this study for vertical and horizontal components were compared to the moment magnitudes from FUNVISIS, a comparison of which can be seen in Figure 13. In general there is good correlation for each component.



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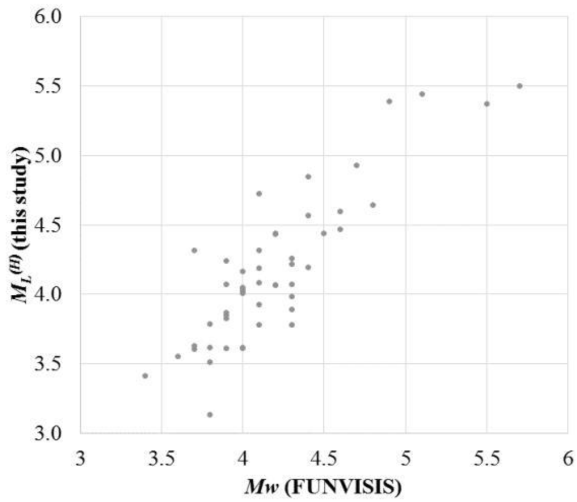

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Figure 13. Comparison between local magnitude from this study and seismic moment magnitude from FUNVISIS for vertical (a) and horizontal (b) components.

In the near future, we plan to expand earthquake data set in order to determine station corrections. By including station corrections within the local magnitude formula, we could be able to improve results. Additionally, with a large number of amplitude data, we could investigate whether amplitudes for vertical and horizontal components agree well as this study showed. In addition, we will be able to evaluate which component is more accurate to estimate local magnitude in Venezuela.

Furthermore, it will be important to include data for small earthquakes. In Venezuela there are several small earthquakes in which magnitudes are not determined by using spectral analysis due to the high noise level. If we can determine more accurate magnitudes for small earthquakes, we will obtain a more comprehensive catalogue, which is important to understand the seismicity precisely. Additionally, improve the estimation of the magnitude for small earthquakes will help in reducing the completeness magnitude of FUNVISIS's catalogue, which in the future will be important in the evaluation of the seismic hazard in Venezuela.

CONCLUSION

We determined local magnitude scales in Venezuela for vertical and horizontal components, respectively. We measured 636 vertical and horizontal peak amplitudes for 50 shallow inland earthquakes that were recorded by 35 broadband stations of the National Seismological Network. The magnitude range is from 3.4 to 5.7. We found a good correlation between maximum amplitudes on vertical component and those on the horizontal component. The average ratio of the horizontal component amplitude to the vertical component amplitude is 1.7.

The local magnitude coefficients for geometrical spreading and anelastic attenuation obtained by linear inversions are 1.031 and 0.00116 for the vertical component and 1.306 and 0.00075 for the horizontal component, respectively. The magnitude residuals calculated for the local magnitude formulas obtained in this study do not show significance dependence on hypocentral distance. We compared local magnitude for both components and found that the local magnitude for the vertical component was small than for the horizontal component by about 0.2 in the magnitude range from 3.2 to 5.5.

In the distance range larger than 100 km, the distance correction functions for Venezuela are lower than that for Central and Southern California, which is adopted for the IASPEI standard formula, and higher than central United States and Norway. When the IASPEI formula is used, M_L are slight overestimates.

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